

GRB afterglow light curves from realistic density profiles

P. Mimica¹^{*} and D. Giannios²

¹*Departamento de Astronomía y Astrofísica, Universidad de Valencia, 46100, Burjassot, Spain*

²*Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA*

13 June 2011

ABSTRACT

The afterglow emission that follows gamma-ray bursts (GRBs) contains valuable information about the circumburst medium and, therefore, about the GRB progenitor. Theoretical studies of GRB blast waves, however, are often limited to simple density profiles for the external medium (mostly constant density and power-law R^{-k} ones). We argue that a large fraction of long-duration GRBs should take place in massive stellar clusters where the circumburst medium is much more complicated. As a case study, we simulate the propagation of a GRB blast wave in a medium shaped by the collision of the winds of O and Wolf-Rayet stars, the typical distance of which is $d \sim 0.1 - 1$ pc. Assuming a spherical blast wave, the afterglow light curve shows a flattening followed by a shallow break on a timescale from hours up to a week after the burst, which is a result of the propagation of the blast wave through the shocked wind region. If the blast wave is collimated, the jet break may, in some cases, become very pronounced with the post break decline of the light curve as steep as t^{-5} . Inverse Compton scattering of ultra-violet photons from the nearby star off energetic electrons in the blast wave leads to a bright \sim GeV afterglow flare that may be detectable by *Fermi*.

Key words: Hydrodynamics – Shock waves – gamma-rays: bursts – radiation mechanisms: nonthermal – radiative transfer

1 INTRODUCTION

The prompt phase of GRBs is followed by a long-lived afterglow emission. The afterglow is believed to be powered by shocks driven by the relativistic outflow into the circumburst medium. Assuming that these external shocks inject ultrarelativistic electrons into the downstream shocked fluid, synchrotron emission from these particles can account for the basic properties of a large number of the afterglow observations (Sari et al. 1998; Wijers & Galama 1999).

Afterglow modeling can provide important information about, among other things, the density profile of the circumburst material, thus constraining the nature of the progenitor. So far, however, typically only very simplistic density profiles have been considered, i.e., the external medium is assumed either to have constant density or to follow a power-law function of spherical distance R . Observations are inconclusive about the density profile, i.e., depending on the burst and the analysis more than one or none of the simple density profiles may account for observations (see, e.g., Panaitescu & Kumar 2002; Piro et al. 2005; Starling et al. 2008; Curran et al. 2003; Schulze et al. 2011).

At least some long-duration GRBs have been convincingly shown to be associated with the death of massive stars of Wolf-Rayet type (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Mazzali et al. 2003). Because Wolf-Rayet stars are characterized by strong winds, a R^{-2} wind-like profile is, at first sight, a

natural choice to describe the density distribution surrounding the progenitor. However, for high enough density of the medium that confines the stellar wind, the termination shock of the wind may take place sufficiently close to the progenitor to affect the afterglow light curve (Wijers 2001; Chevalier et al. 2004; Ramirez-Ruiz et al. 2005; Pe’er & Wijers 2006).

The actual density profile which decelerates the GRB-driven blast wave could be much more complicated. Massive stars rarely form in isolation; they preferentially reside in dense stellar clusters where tens or even hundreds Wolf-Rayet and O stars are crowded on sub-pc scale regions (e.g. Massey & Hunter 1998). About *one third* of the Galactic Wolf-Rayet stars are located in several very massive stellar clusters (e.g., Figer 2004). It is reasonable to expect a fair fraction of GRBs to take place in such dense stellar environment. The interactions of the strong stellar winds in stellar clusters complicate the medium that surrounds the GRB progenitor and, therefore, the blast wave evolution. Furthermore, nearby O stars provide a strong UV photon field that is up-scattered by electrons accelerated at the forward shock and may potentially result in bright GeV afterglow flaring (Giannios 2008).

As a first step towards studying the afterglow appearance in more realistic density profiles, we focus on a blast wave propagating through a medium shaped by colliding stellar winds. Hydrodynamic simulations are used to study the profile from the collision of stellar winds. Follow-up relativistic hydrodynamic simulations are performed in order to study the blast wave propagation through such density profile (Section 2). The fluid dynamics are coupled

^{*} E-mail: Petar.Mimica@uv.es

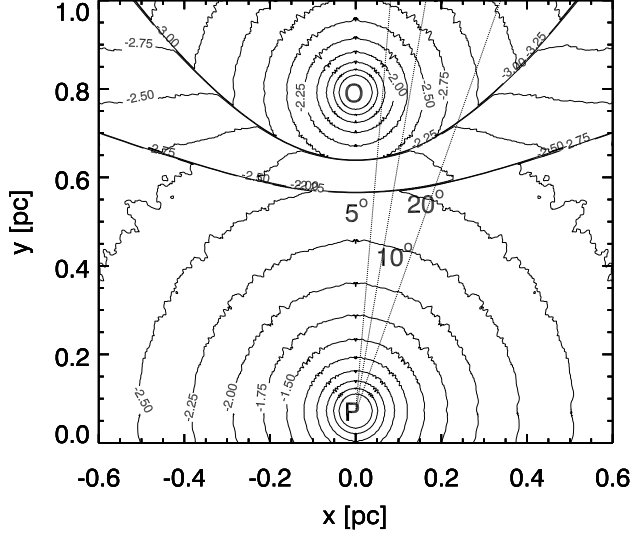


Figure 1. Contours of the logarithm of the gas density (in arbitrary units) in the vicinity of the progenitor (P) and the O star. The contour values are decreasing in steps of 0.25 as one moves away from the stars. The shocked stellar winds are located in the region between two thick arcs, which are the termination shocks for the progenitor and O star winds. The three lines show the cuts at angles 5, 10 and 20 degrees from the line joining the centers of the two stars, respectively.

to a radiative transfer code to calculate the resulting synchrotron and inverse Compton emission (Sections 3 and 4). We discuss our results in Section 5.

2 A BLAST WAVE IN COMPLEX DENSITY PROFILES

With the number of massive stars $N_* \sim 100$ (ranging from a few tens to a few hundreds) crowded on a $R_c \lesssim 1$ pc scale of a typical massive stellar cluster (similar to, e.g., Westerlund 1, Arches, Quintuplet, or Center in the Galaxy), the mean distance between O stars is $d \sim R_c/N_*^{1/3} \sim 0.1$ pc. The blast wave driven by a GRB, still relativistic at these distances, is expected to encounter density bumps while propagating in the cluster. We simulate several density profiles that may be expected in a massive cluster and then study the blast wave propagation through them.

2.1 Colliding winds

In the young stellar cluster under consideration, the gas density is shaped by the interactions of the stellar winds. Since the most massive (O and Wolf-Rayet) stars have the strongest winds, they are going to dominate these interactions. The stars are surrounded by regions of their freely expanding winds that are followed, further out, by regions of shocked gas—result of wind-wind collisions. For a given line of sight from the explosion center to the observer, the density is likely to be shaped by the few massive stars that happen to lie close to it. For N_* stars randomly distributed in the cluster, the closest one to the line of sight of the observer is located at an angle $\theta \sim (4/N_*)^{1/2} \sim 0.2N_{*,2}^{-1/2}$ rad (where the $A = 10^A A_X$ notation is adopted). Encountering a star within an angle $\theta \sim 10^\circ$ from the line of sight is, therefore, the norm in the massive clusters under consideration. As long as the outflow is ultrarelativistic with a bulk Lorentz factor $\Gamma \gg 1$, the observer of the GRB afterglow probes the blast-medium interactions that take place within a narrow cone

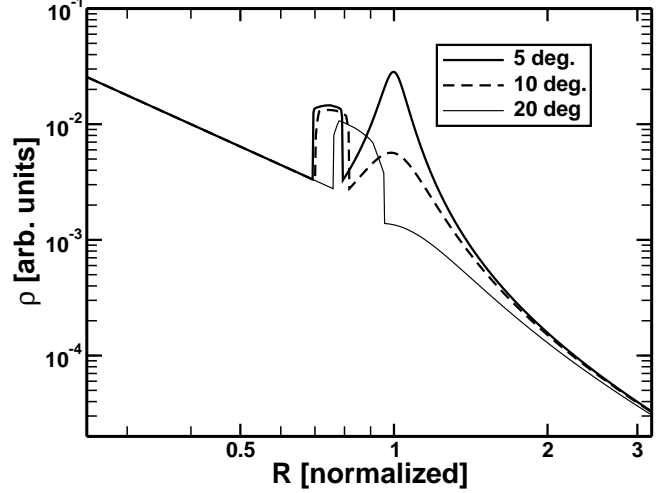


Figure 2. Density profiles along the cuts at $\theta = 5, 10$ and 20 degrees from the line joining the centers of the two stars on Fig. 1. The radius R is measured from the center of the progenitor and is normalized to the distance between the stars.

of angle $\sim 1/\Gamma$ with respect to the line of sight. In the narrow cone which the observer can see the closest stellar encounter is the dominant one in determining the relevant density profile.

As a first approach, we limit ourselves to a single massive star (O) located at distance $d \lesssim 1$ pc from the explosion center (P) and at a modest angle $\theta \lesssim 0.5$ rad with respect to the line that connects the explosion center to the observer (Fig. 1). We consider the density profile resulting from the collision of the winds of two stars with mass loss rates $\dot{M}_P = 10^{-5} M_\odot \text{yr}^{-1}$ and $\dot{M}_O = 10^{-6} M_\odot \text{yr}^{-1}$, respectively. The \dot{M}_P is typical for a Wolf-Rayet star assumed to be the GRB progenitor, and \dot{M}_O is expected for a typical O star (also referred to as the ‘companion’ star). The stellar winds are assumed to be cold and have the same velocity $v_w = 1000 \text{ km s}^{-1}$. We have performed a 2-dimensional (2D) axisymmetric hydrodynamical simulation of such wind-wind interaction assuming adiabatic behaviour of the gas¹. We have used the high-resolution shock-capturing scheme *MARGENESIS* (Mimica et al. 2007, 2009b) to run the simulation until a steady state is established. The numerical resolution is 800 and 2400 cells in x and y directions, respectively.

In Fig. 1, we show the density contours from such interaction. The regions of freely expanding winds and shocked winds are clearly seen. Because of the choice of the same velocity v_w for the two winds, there is no contact discontinuity separating the two shocked winds (see Stevens et al. 1992). The shocked wind region lies closer (and bends toward to) the O star because $\dot{M}_P > \dot{M}_O$.

In Fig. 2, we plot the density profile moving radially outwards from the Wolf-Rayet star and for different angles with respect to the O star. The density profiles are averaged over a cone with opening angle of 5 degrees. One can see the R^{-2} density profile from the progenitor, a narrow region of enhanced density due to the shocked colliding winds and, at larger distance the freely expanding wind of the companion. These profiles are used as the density of the external medium through which the GRB blast wave propagates.

¹ Stevens et al. (1992) and, more recently, van Marle et al. (2011) have studied the stellar wind interaction in detail and showed that for the distances $d \gtrsim 0.1$ pc of interest here, radiative cooling in the shocked regions is negligible, thus justifying the assumption that the gas is adiabatic.

2.2 Blast wave propagation

For characteristic distance $d \gtrsim 10^{17}$ cm between the stars considered here, the blast wave has evolved into a self-similar (Blandford & McKee 1976) stage before encountering the shocked wind region. As long as the bulk Lorentz factor of the shocked fluid is larger than the inverse opening angle of the jet: $\Gamma \gtrsim \theta_j^{-1}$, 2D effects (e.g. lateral jet spreading) can be safely neglected. In this regime, the blast wave can be studied assuming a spherically symmetric evolution. We follow the evolution of the blast wave with 1D relativistic hydrodynamic simulations (Mimica et al. 2009b). We caution, however, that by the end of our simulations, the fluid may decelerate to $\Gamma \sim$ several and lateral spreading effects (not taken into account by our simulations) may be modestly important for $\theta_j \sim 0.1$; a value commonly inferred in GRBs (Frail et al. 2001). This point is discussed further in Section 3.1.

Having specified the density profile for the external medium, we only need to choose the (isotropic equivalent) energy of the blast E for the self-similar initial conditions to be well defined. We consider a rather powerful GRB of $E = 10^{54}$ erg. The distance between the stars is set to $d = 2.2 \times 10^{18}$ cm. The blast wave dynamics is followed with relativistic hydrodynamic simulations using the code *MARGENESIS* described in Mimica et al. (2009b). The simulations have been performed in spherical symmetry with a numerical resolution of 16000 cells in the blast wave. We have generated five blast wave models:

- three models with external medium density profiles shown in Fig. 2: *N05* (cut along a line 5 degrees off the line joining centers of two stars), *N10* (10 degrees) and *N20* (20 degrees)
- a simulation in an external medium with a wind profile throughout: model *WP*
- a simulation in an external medium with a wind profile out to the wind termination shock (TS) at 1.6×10^{18} cm (we assume a density jump of factor 4 at the TS and a constant density medium afterwards): model *TS*

In Fig. 3, we show the Lorentz factor of the fluid at the forward shock as function of distance from the center of the explosion. The initial evolution of all models is that of a self-similar blast in a R^{-2} wind profile where the Lorentz factor just behind the forward shock $\Gamma \propto R^{-1/2}$ (Blandford & McKee 1976). For models *N05*, *N10* and *N20* the self-similar evolution holds until distance $R \sim d$ where the blast encounters the region of the shocked winds. At this stage, the enhancement of the density causes the forward shock to decelerate and a weak reverse shock launches into the blast. On exit from the shocked wind region, the density drops and the blast rarefies in the front. The density profile has a second bump due to the approach to the companion star. This results in one more drop in the Lorentz factor Γ , the depth of which depends on the angle θ . These non self-similar stages of the interaction can only be studied in detail using numerical simulations. At still larger distance the blast wave relaxes to a self-similar solution determined by the R^{-2} density profile of the companion star. In the model *WP* the blast wave follows the Blandford & McKee (1976) evolution, while in the model *TS* it decelerates much faster after encountering the constant density medium behind the termination shock (e.g. van Eerten et al. 2009).

3 EMISSION

After the hydrodynamical simulations have been performed we use the *SPEV* code (Mimica et al. 2009a) to compute the light curves.

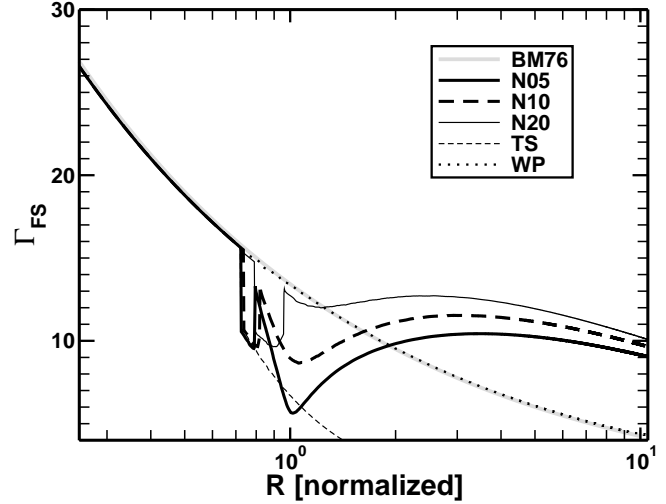


Figure 3. Lorentz factor of the shocked fluid behind the forward shock as a function of the distance from the progenitor for a blast wave propagating at an angle $\theta = 5, 10$ and 20 degrees (thick full, thick dashed and thin full lines, respectively) from the line joining centers of the two stars (see also Fig. 1). Also shown is the evolution of the Lorentz factor in a wind profile (dotted line), the Blandford & McKee (1976) analytic solution for a wind profile (thick gray line closely following the dotted line) and the evolution in a wind profile with the termination shock (thin dashed line). The distance is normalized to the separation of the two stars.

The details of how *SPEV* is applied to calculate the afterglows from GRBs can be found in the section 3 of Mimica et al. (2010). We consider synchrotron emission from the shock-accelerated electrons (Sect. 3.1) and external inverse Compton scattering of the photon field from the companion star off the same electrons (Sect. 3.2). In this paper we ignore the synchrotron self Compton process. Sect. 3 contains qualitative discussion and analytical estimates while the numerical results are presented in Sect. 4.

3.1 Synchrotron emission

During the initial self-similar stage of deceleration in the wind of the progenitor of density $\rho = A/R^2$, with $A \equiv \dot{M}_p/4\pi v_w = 5 \times 10^{11} A_* \text{ gr cm}^{-1}$ where $A_* = \dot{M}_{-5} v_{w,8}^{-1}$, the bulk Lorentz factor of the fluid just behind the shock is

$$\Gamma = \sqrt{\frac{9E}{16\pi A R c^2}} = 60 E_{54}^{1/2} R_{17}^{-1/2} A_*^{-1/2}. \quad (1)$$

The observer time evolves as $t_{\text{obs}} = R/2\Gamma^2 c \approx 500 R_{17}^2 A_* E_{54}^{-1}$ s (neglecting cosmological redshift effects). For the distance $d \sim 3 \times 10^{17}$ cm and the energy $E \sim 10^{53}$ erg, it takes typically a day for the blast wave to reach the shocked wind region (this timescale can range from hours to a week, depending on the various parameters).

We make standard assumptions in calculating the synchrotron emission from shocked fluid in the blast wave following Sari et al. (1998), i.e., we assume that a fraction ϵ_e , and ϵ_B of the dissipated energy goes into accelerating electrons into a power-law distribution with index p and amplifying magnetic field, respectively. Throughout this paper we fix $\epsilon_e = 0.1$, $\epsilon_B = 0.005$, and $p = 2.5$. The light curve at the initial self-similar stage is that calculated by Chevalier & Li (2000) that focus on a blast propagating in a R^{-2} wind profile. At a time $t_{\text{obs}} \sim d/\Gamma^2 c$ the blast wave encounters the region of the shocked winds, which encounter causes a flattening in the light curve (Fig. 4). This feature has already been discussed

in the case of a wind with a termination shock (Nakar & Granot 2007; van Eerten et al. 2009). In our setup, the blast wave crosses the shocked wind region on a short timescale and transits to a less dense wind of the companion. This transition, a distinct characteristic of colliding stellar winds, leads to a steeper decline of the light curve. More light curves and a discussion are presented in the next section.

In our 1D, spherically symmetric approximation, even the sharp features of the external medium (e.g. shocks, density jumps) result in smooth changes on the afterglow emission. This effect, result (at least in part) of the large lateral extent of the emitting region, has been studied in detail by Nakar & Granot (2007) and van Eerten et al. (2009). However, there is good evidence that GRB jets are collimated with opening angles of $\theta_j \sim 0.1$ (e.g. Frail et al. 2001). Here we show that departures from spherical symmetry combined with structured external media introduce interesting novel features to the afterglow light curves.

In addition to modulations of the light curve because of external density profile, deviations from spherical symmetry are also expected to affect the afterglow appearance. A ‘jet break’ in the light curve is expected to occur when $\Gamma \sim \theta_j^{-1}$ for a smooth density profile (Rhoads 1999). Zhang & MacFadyen (2009) have shown that the main effect of the $\Gamma \lesssim \theta_j^{-1}$ transition is a steepening in the light curve because of the ‘missing surface’ emitting towards the observer (see, however Wygoda et al. 2011). With our 1D simulations we cannot treat the transition exactly. However, we can easily include the dominant geometric effect that contributes to the jet break by considering the emission taking place only within an angle θ_j with respect to the observer. Such examples are shown in Fig. 5 and discussed in Section 4.1.

3.2 Compton scattering of the photons from the companion

When the blast wave approaches the companion, it is exposed to the dense UV field of the O star. Electrons accelerated at the shock will Compton up-scatter the stellar light to (typically) GeV energies. Such encounter leads to a GeV flare hours to days after the GRB (the time of closer approach to the star) that is potentially detectable with *Fermi*. Giannios (2008) analytically derived the γ -ray fluence from a blast wave sweeping past the photon field of an O star for constant density ISM. Here we repeat the derivation for the wind profile, so that a comparison of the analytical estimates to more accurate numerical results can be done (Section 4.2). In addition to the model of Giannios (2008), we consider the contribution of the ambient UV photon field of the cluster to the external inverse Compton (EIC) scattering of blast wave electrons.

We consider an O star of $L_* \sim 10^6 L_\odot \sim 10^{39.5} L_{39.5} \text{ erg s}^{-1}$ located at a distance d from the progenitor, and at an angle θ with respect to the line of sight. The emission of the star is assumed to peak at $e_* = 10e_{*,1} \text{ eV}$ (typical for an O star). Electrons accelerated at the forward shock have a lower cut-off of their distribution at $\gamma_{\min} \simeq (\epsilon_e/3)\Gamma(m_p/m_e) \simeq 1000\epsilon_{e,-1}E_{54}^{1/2}d_{18}^{-1/2}A_*^{-1/2}$, where Eq. 1 is used in the last step. The energy of the scattered photons in the central engine frame is

$$e_{\text{ic}} \simeq 2\Gamma^2\gamma_{\min}^2 e_* = 8 \frac{\epsilon_{e,-1}^2 E_{54}^2 e_{*,1}}{d_{18}^2 A_*^2} \text{ GeV}. \quad (2)$$

The detailed numerical results (Section 4.2) identify the expression e_{ic} as a good estimate for the peak of the L_ν spectrum of the EIC component. Note that for $e_{\text{ic}} \gtrsim (m_e c^2)^2/e_* \simeq 25/e_{*,1} \text{ GeV}$, the scattering takes place in the Klein-Nishina regime for all electrons and the last expression is not applicable.

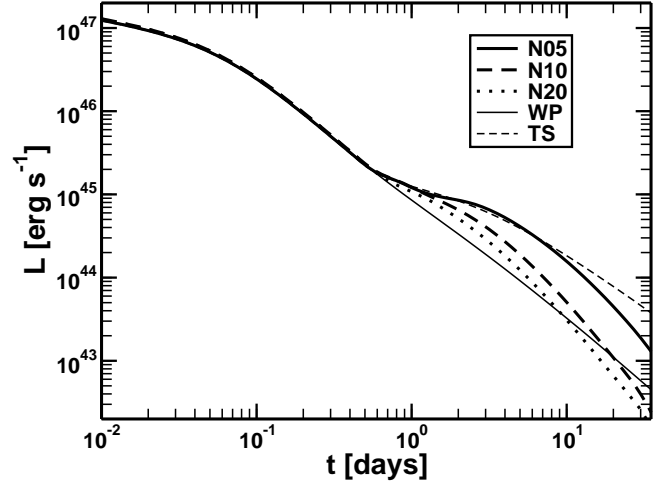


Figure 4. R-band ($\nu = 4.3 \times 10^{14} \text{ Hz}$) light curves for the five numerical models. Their light curves are indistinguishable until ≈ 0.5 days, at which point the light curve of all the models which contain a shock (i.e., N05, N10, N20 and TS) flattens. The TS light curve soon reaches the asymptotic behavior expected of the blast wave propagating into a homogeneous external medium (see e.g., Fig. 2 of van Eerten et al. 2009). The light curves of the remaining three models show a more complex behaviour due to the crossing over a second wind termination shock. The crossing point depends on the angle at which the blast wave is propagating, which is reflected in the different late-time light curves for N05, N10 and N20 models.

The fluence of the EIC component can be estimated by considering the fraction of the total energy carried by electrons $\epsilon_e E$ that is radiated away because of EIC. The closest approach to the companion star is $\sim \theta d$ with the energy density of photons (in the rest frame of the blast wave) being $U_{\text{ph}} \simeq \Gamma^2 L_* / 4\pi(\theta d)^2 c$. The IC cooling timescale of an electron with γ_{\min} is $t_{\text{cool}} = 2 \times 10^7 / \gamma_{\min} U_{\text{ph}} \text{ s}$. The energy density of external photons peaks while the blast travels distance $d\theta/\Gamma$ (in the comoving frame of the blast). The residence time in the intense radiation field is, therefore, $t_{\text{res}} = r\theta/\Gamma c$. Combining all these, we obtain the fluence of the IC component:

$$F_{\text{ic}} = \frac{t_{\text{res}}}{t_{\text{cool}}} \epsilon_e E = 5 \times 10^{50} \frac{\epsilon_{e,1}^2 E_{54}^2 L_{39.5}}{\theta_{-1} d_{18}^2 A_*} \text{ erg}. \quad (3)$$

The detailed numerical results (see Section 4.2) show that expression for F_{ic} overestimates the fluence of the EIC component by a factor of, typically, \sim a few. Klein-Nishina corrections contribute mostly to the discrepancy.

The flare peaks at time

$$t_{\text{peak}} = d/2\Gamma^2 c \simeq 0.5 d_{18}^2 A_* E_{54}^{-1} \text{ days}. \quad (4)$$

Note that for $d \sim 3 \times 10^{17} \text{ cm}$, $A_* \lesssim 1$, a close encounter with a bright star leads to extraction of a large fraction of the electron energy in the blast through EIC scattering. The emission from such encounter may peak several hours after the burst.

4 LIGHT CURVES

In this section we present the light curves produced by the five models introduced in the section 2.2. We first discuss the optical, X-ray light curves result of synchrotron emission, and then turn our attention to the γ -ray emission result of EIC.

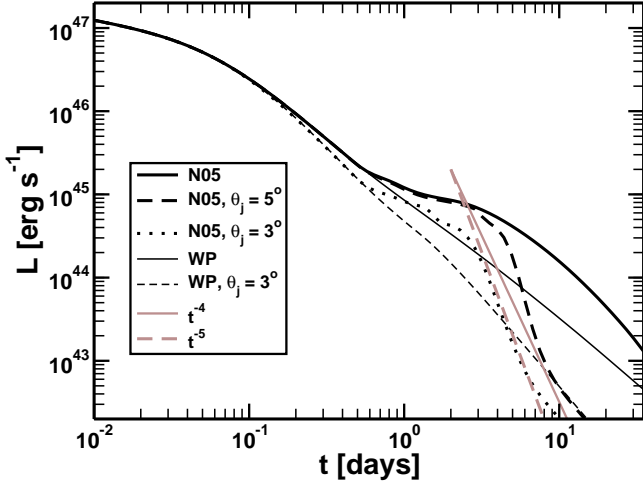


Figure 5. Same as Fig. 4, but for models where various jet opening angles have been assumed. Shown are the light curves of the *N05* model assuming a spherical blast-wave (thick line), and assuming a jet half-opening angle of 5° and 3° (thick dashed and dotted lines, respectively). For comparison we show the light curve in a wind environment for the spherical outflow and a jet half-opening angle of 3° (thin full and dashed lines, respectively), and two curves showing the decline proportional to t^{-4} and t^{-5} (gray full and dashed lines, respectively).

4.1 Optical/X-ray emission

Fig. 4 shows the optical light curves. Before reaching the progenitor wind termination shock the light curves are indistinguishable from the one corresponding to a self-similar blast wave propagating in a R^{-2} profile (model *WP*). From that point on the models begin to diverge depending on whether the blast wave continues propagating into a constant-density environment (*TS*) or whether it eventually encounters the wind of the companion star (*N05*, *N10* and *N20*). The latter three models differ in their light curves because the blast wave crosses the wind interaction zone and a companion stellar wind at different angles.

In model *N05* the blast wave propagates closest to the companion star and it encounters the densest companion wind. Therefore it is slowed down more than *N10*, which in turn decelerates more than *N20* (see also Fig. 3). This is seen in Fig. 4 after $t \simeq 3$ days, where *N05* is the brightest of the three models, followed by *N10* and *N20*.

Fig. 5 shows the effect of the finite opening angle of the jet. Since we are simulating a one-dimensional spherical blast wave, we model a jet with a half-opening angle θ_j by assuming no contribution to emission from the fluid at angle with respect to the line of sight $> \theta_j$. As expected, while $\Gamma \gtrsim \theta_j^{-1}$ the jet collimation is not affecting the light curve. For a blast wave propagating in a pure wind-like profile, a rather smooth break appears in the light curve when $\Gamma \sim \theta_j^{-1}$. The break can be much sharper if the transition to $\Gamma < \theta_j^{-1}$ takes place when the blast wave reaches the shocked wind region. The rapid decline of the Lorentz factor of the blast wave at the density jump is not compensated by the increase of the emitting surface visible to the observer and the flux drops much faster than expected from a jet break in a smooth external medium. Comparing with the thick full and dashed gray lines (which show the temporal decline proportional to t^{-4} and t^{-5} , respectively), we see that the combination of the jet break and the interaction of the blast wave with a shocked wind environment can produce steep declines.

Fig. 5 shows also demonstrates how the break happens at pro-

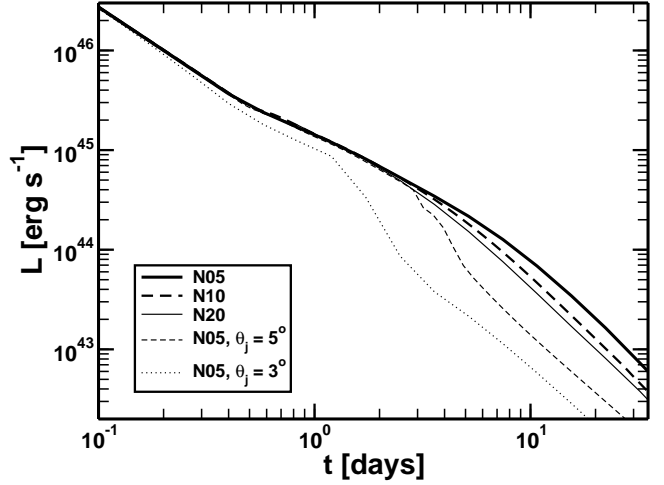


Figure 6. 1 keV X-ray light curve for the models *N05*, *N10* and *N20* (thick full, dashed and dotted lines, respectively). Shown are also two cases for the model *N05* if we assume a jet half-opening angle of 5° and 3° (thin dashed and dotted lines, respectively).

gressively earlier times as θ_j is decreases (thick full, dashed and dotted lines, respectively). At later times the light curve decline becomes less steep due to the acceleration of the blast wave as it leaves the shocked region and encounters a less dense companion stellar wind.

Fig. 6 shows the X-ray light curve for the models *N05*, *N10* and *N20*, as well as for the model *N05* assuming a small jet opening angle, to simulate the effect of a jet break. As can be seen, the effect of the traversal of the shocked wind leaves qualitatively similar but less pronounced imprints on the X-rays in comparison to the optical light curve (see Fig. 4). The effect of the jet break (result of a finite jet angle) is, as expected, also an adiabatic one (e.g., not due to electron cooling), appearing in simultaneously in the optical and X-rays.

4.2 γ -ray emission

The analytical estimates of Section 3.2 provide the dependence of the photon energy and fluence (e_{ic} and F_{ic} , respectively) of the EIC emission on the various parameters. The actual numerical values of Eqs. 2 and 3 are, however, meant more as rough order-of-magnitude estimates than the accurate predictions. In this section we use the numerical simulations to calculate the EIC emission and calibrate the analytics.

Part of the uncertainty of the analytical estimates is connected to the fact that they ignore the blast wave hydrodynamics of the shocked wind regions (instead, the blast wave is assumed to propagate in a freely propagating stellar wind). The numerical simulations are more accurate since they include the effect of the colliding winds on the blast dynamics and the exact calculation of the EIC cooling during the blast encounter (including Klein-Nishina effects) for a power-law injected electron distribution. We compute the EIC emission assuming a monochromatic external point-source of radiation (good approximation for the black body stellar emission). To compute the emissivity we use the method described in the section 2.2.1 of Mimica (2004).²

² This enables us to use the same piecewise power-law representation of the non-thermal electron distribution that *SPEX* uses to compute synchrotron

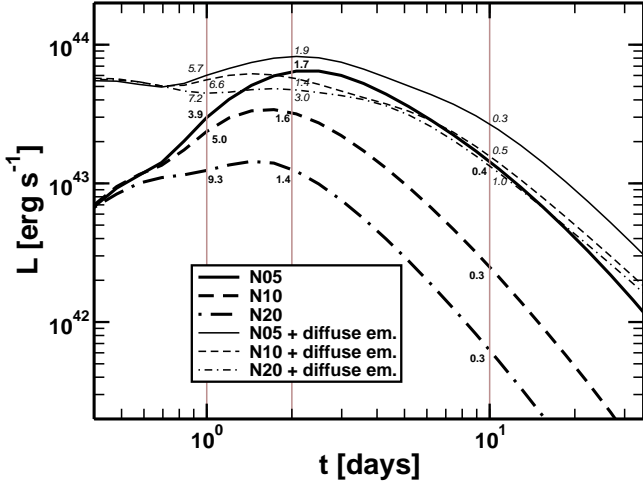


Figure 7. Bolometric (4 MeV - 4 TeV) light curves from external inverse Compton scattering for the models *N05*, *N10* and *N20* (full, dashed and dotted lines, respectively). The thick lines show the light curves assuming that the only source of photons is the companion star. The numbers in bold show the energy of the spectral peak in GeV for radiation observed 1, 2, and 10 days after the burst. The thin lines show the emission when the diffuse cluster emission is taken into account as a soft-photon source (see text for details). The numbers in italic denote the spectral peak in GeV for this case.

Fig. 7 shows the EIC bolometric light curves and the energy of the spectral peak (in GeV) for the models *N05*, *N10* and *N20* (thick full, dashed and dotted lines, respectively). The EIC emission peaks at time $t_{\text{peak}} \sim 2$ days in good agreement to Eq. 4 (using the value $d_{18} = 2.2$) and then gradually declines. The duration of the high energy flare is $\delta t \sim t_{\text{peak}}$. As expected, the EIC is brighter for the closer encounters (smaller θ) between the line of sight and the companion star. At maximum of the EIC luminosity the peak of the L_ν spectrum is $E \approx 2$ GeV independently of θ in close agreement to Eq. 2. The spectral peak moves to lower energies as function of time. We have verified that the EIC spectrum has a cutoff at ~ 25 GeV because of the Klein-Nishina suppression. The numerically calculated fluence is found to be a factor of ~ 3 less than the estimate in Eq. 3.

The total number of γ -ray photons emitted in the 0.1-300 GeV energy range (where the effective area of *Fermi-LAT* peaks) is $N_\gamma \approx 8 \times 10^{51}$, 2×10^{51} , 6×10^{50} for $\theta = 5^\circ$, 10° , 20° , respectively. For an effective area of *LAT* of $A_{\text{eff}} \sim 10^4$ cm², the closest encounter can be detected out to a proper distance of $d_p \approx (A_{\text{eff}} N_\gamma / 4\pi)^{1/2} \approx 2.5 \times 10^{27}$ cm or out to a modest redshift of $z \sim 0.3$ for this example.

In addition to the photon field of the companion, the blast wave also encounters the diffuse emission of the stellar cluster. The latter is dominated by that of the most massive stars in the cluster. For N_* massive stars of luminosity L_* each distributed isotropically within a cluster of radius R_c , the ambient UV photon field in the cluster is $U_{\text{UV}} \sim 3N_* L_* / 4\pi R_c^2 c$. Fig. 7 shows the total EIC emission coming from the scattering of the photon field of the companion and the ambient cluster emission for $N_* = 30$, $L_* = 10^{39.5}$ erg s⁻¹, and $R_c = 5 \times 10^{18}$ cm (thin lines). Note that the ambient photon field is the dominant source of soft photons for the more distant encounters (with $\theta = 10, 20$ deg) while it makes a modest contribution to the $\theta = 5$ deg example. The peak of the EIC component is broader

in this case. Including both the companion and the diffuse sources of soft photons, the total number of γ -ray photons emitted in the 0.1-300 GeV energy range increases to $N_\gamma \approx 1.4 \times 10^{52}$, 8×10^{51} , 6×10^{51} for $\theta = 5^\circ, 10^\circ, 20^\circ$, respectively. In this case the emission can be detected out to $d_p \approx 3.3 \times 10^{27}$ cm, or out to $z \sim 0.3 - 0.4$.

5 DISCUSSION

If all, or at least the majority of, long duration GRBs come from the death of massive stars, a fair fraction of them should take place inside young, massive stellar clusters. In such crowded environments the wind of the progenitor star terminates on sub-pc scales (mainly due to interactions with other stellar winds). The wind-wind interaction regions are characterized by shocks, contact discontinuities and other sharp features in the density profile. The blast wave, result of the GRB jet interacting with the external medium, has a bumpy ride in such environments. In this work we search for the characteristic observational signatures of such blast wave evolution, focusing on the profile shaped by the collision of the wind of the progenitor with that of a nearby massive star or ‘companion’.

5.1 Optical and X-ray emission

As long as the Lorentz factor of the blast $\Gamma \gg 1$ and $\Gamma \gtrsim \theta_j^{-1}$, one can study the basic features of the blast-external medium interaction assuming spherical symmetry and considering different lines of sight to the observer. We find that, when the blast wave enters the shocked wind region, the optical light curve at first flattens, followed by a steeper decline at later times (Fig. 4). When the characteristic synchrotron frequency crosses the observed band, the modulations of the light curve are enhanced. Qualitatively similar (but much less pronounced effects) are in general expected in the X-rays as well (Fig. 6). Our results are in agreement with the generic arguments presented in Nakar & Granot (2007), who show that relativistic blast waves in spherical symmetry do not show sharp features in their light curve even for step-function changes of the external density as function of radius.

Observations with dense sampling until late times and good signal-to-noise are required to detect the relatively smooth changes in the light curves. One recent example is a well studied optical, X-ray afterglow of GRB 080413B (Filgas et al. 2011), which shows a characteristic flattening in the optical followed by a steeper decline in both optical and X-ray wavelengths that appears to be in agreement with the expectations from our model. Further examples include GRBs 021004 (see Lazzati et al. (2002) and references therein), 080710 (Krühler et al. 2009a), 080129 (Greiner et al. 2009a) and 080913 (Greiner et al. 2009b). Finally, there is an interesting GRB 071031 (Krühler et al. 2009b), which shows several bumps in the optical, which might be due to more than one star influencing the afterglow (see, however, the discussion in Sec. 5.3).

For a wide range of parameters, the blast wave is expected to enter the shocked wind region when $\Gamma \sim \theta_j^{-1}$. Strictly speaking, our 1D calculations are not directly applicable to this regime since they ignore lateral spreading of the blast. Nevertheless, recent 2D simulations performed by Zhang & MacFadyen (2009) indicate that lateral spreading effects are small at this stage and that the ‘jet breaks’ are mainly a geometric effect. We show that the combination of jet collimation and structured external medium may lead to the rather sharp features in the light curve, such as a fast decline of

the light curve as steep as $F \propto t^{-4 \dots -5}$, which is not expected for the evolution in a smooth external medium (Fig. 5).

5.2 γ -ray emission

Another characteristic signature of the companion-blast interaction is an inverse-Compton powered, GeV flare (Giannios 2008). We show that, under optimistic conditions, a large fraction of the energy deposited on the shocked electrons is radiated away during the encounter with the dense UV photon field of the massive star. Such a flare at the energies of tens of GeV may account e.g., for the emission of the GRB 940217 observed hours after the burst with *EGRET* (Hurley 1994). The *LAT* instrument on-board to the *Fermi* satellite is capable of detecting such flaring for bursts out to modest redshift $z \lesssim 1$. Depending of the distance of the companion star, the \sim GeV emission will peak on timescales that range from a few hours up to a few weeks after the burst (Fig. 7). In some cases, the *ambient* UV photon field of the massive stars in the cluster may be the dominant source of the external inverse Compton component resulting in slower varying γ -ray emission. A systematic search for delayed γ -ray emission from the location of the burst on timescales of hours to weeks after the burst may be fruitful. The timing and photon-energy of such detection will provide invaluable information about the GRB environment.

An additional promising source of seed photons to be inverse Compton scattered at the forward shock may be the infrared emission from dust. Though its physical origin is unclear, dust is forming actively in the stellar (or shocked) wind region in many Wolf-Rayet stars (e.g., Crowther 2003). Up to $\sim 10\%$ of the stellar light can be reprocessed into the infrared that provides an isotropic bath of photons through which the blast propagates. Mid-to-near infrared photons can be scattered into multi TeV energies by the high-energy tail of the electron distribution while still in the Thomson scattering regime. Such emission, with a $\nu \cdot L_\nu$ peak at \sim TeV energies, may be detectable by atmospheric Cherenkov telescopes provided that the burst takes place at redshift $z \lesssim 0.5$ (for the TeV photons to avoid attenuation while propagating through the extragalactic background light).

5.3 Other effects

In this paper, we focused on the effect of a *single* massive star on the circumburst medium density in the cluster where the GRB takes place. This star is most relevant in the early afterglow stages since it lies the closest to the line of sight to the observer. Clearly, the collective effect of many stellar winds will dominate the density profile at larger distance (more than a few times the distance to the ‘companion’). At these scales the external medium is expected to be very inhomogeneous, although on scales much smaller than those relevant for the blast wave emitting toward the observer. At late times, therefore, the afterglow light curve may resemble that expected from a constant density medium. The confining effect of the environment in the cluster can thus naturally limit the extend of the wind of the progenitor and lead to a constant-like density as is commonly suggested by modeling of afterglow observations (e.g., see Schulze et al. 2011).

ACKNOWLEDGMENTS

We are grateful to Miguel Angel Aloy, Jose María Ibáñez, and Jochen Greiner for the constructive criticism and a fruitful discus-

sion. PM acknowledges the support from the European Research Council (grant CAMAP-259276), from the Spanish Ministry of Education and Science (AYA2007-67626-C03-01, AYA2010-21097-C03-01, CSD2007-00050) and from the Valencian Conselleria d’Educació (PROMETEO/2009/103). DG is a Lyman Spitzer, Jr Fellow of the Department of Astrophysical Sciences of Princeton University. The calculations have been performed on the *Lluís Vives* cluster at the University of Valencia.

REFERENCES

- Blandford R. D., McKee C. F., 1976, *Physics of Fluids*, 19, 1130
- Chevalier R. A., Li Z.-Y., 2000, *ApJ*, 536, 195
- Chevalier R. A., Li Z.-Y., Fransson C., 2004, *ApJ*, 606, 369
- Crowther P. A., 2003, *Ap&SS*
- Curran P. A., Starling R. L. C., van der Horst A. J., Wijers R. A. M. J., 2009, *MNRAS*, 395, 580
- Figer D. F., 2004, *ASPC*, 322, 49
- Filgas, R., et al. 2011, *A&A*, 526, A113
- Frail D. A. et al., 2001, *ApJL*, 562, L55
- Galama T. J., et al., 1998, *Nature* 395, 670
- Giannios D., 2008, *A&A*, 488, L55
- Greiner, J., et al., 2009a, *ApJ*, 693, 1912
- Greiner, J., et al., 2009b, *ApJ*, 693, 1610
- Hjorth J., et al., 2003, *Nature*, 423, 847
- Hurley K., et al., 1994, *Nature*, 372, 652
- Krüehler, T., et al., 2009a, *A&A*, 508, 593
- Krüehler, T., et al., 2009b, *ApJ*, 697, 758
- Lazzati D., Rossi E., Covino S., Ghisellini G., Malesani D., 2002, *A&A*, 396, L5
- Massey P., Hunter D. A., 1998, *ApJ*, 493, 180
- Mazzali, P. A., et al., 2003, *ApJL*, 599, L95
- Mimica P., 2004, Ph.D Thesis, LMU-München
- Mimica P., Aloy M. A., Müller E., 2007, *A&A*, 466, 93
- Mimica P., Aloy M. A., Agudo I., Martí J. M., Gómez J. L., Miralles J. A., 2009a, *ApJ*, 696, 1142
- Mimica P., Giannios D., Aloy M. A., 2009b, *A&A*, 494, 879
- Mimica P., Giannios D., Aloy M. A., 2010, *MNRAS*, 407, 2501
- Nakar E., Granot J., 2007, *MNRAS*, 380, 1744
- Panaiteescu A., Kumar P., 2002, *ApJ*, 571, 779
- Pe’er A., Wijers R. A. M. J., 2006, *ApJ*, 643, 1036
- Piro L., et al., 2005, *ApJ*, 623, 314
- Ramirez-Ruiz E., García-Segura G., Salmonson J. D., Pérez-Rendón B., 2005, *ApJ*, 631, 435
- Rhoads J. E., 1999, *ApJ*, 525, 737
- Sari R., Piran T., Narayan R., 1998, *ApJL*, 494, L17
- Schulze S., et al., 2010, *A&A*, 526, A23
- Stanek K. Z., et al., 2003, *ApJ*, 591, L17
- Starling R. L. C., van der Horst A. J., Rol E., Wijers R. A. M. J., Kouveliotou C., Wiersema K., Curran P. A., Weltevrede P., 2008, *ApJ*, 672, 433
- Stevens I. R., Blondin J. M., Pollock A. M. T., 1992, *ApJ*, 386, 265
- van Eerten H. J., Meliani Z., Wijers R. A. M. J., Keppens R., 2009, *MNRAS*, 398, L63
- van Marle A. J., Keppens R., Meliani Z., 2011, *A&A*, 527, A3
- Wijers R. A. M. J., Galama T. J., 1999, *ApJ*, 523, 177
- Wijers, R. A. M. J. 2001, *Gamma Ray Bursts in the Afterglow Era*, ed. E. Costa, F. Frontera, & J. Hjorth (Springer: Berlin), 306
- Wygoda N., Waxman E., Frail D., 2011, arXiv:1102.5618
- Zhang W., MacFadyen A., 2009, *ApJ*, 698, 1261